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FAILURE MODES FOR IN PLANE LOADED MASONRY WALLS MADE WITH THIN LAYER MORTAR

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ABSTRACT

New technologies for the construction of reinforced and unreinforced masonry buildings, based on the production of new blocks, are being employed and developed and are recognized by the modern generation of codes. While the use of reinforced masonry is accepted and has been purposely developed for buildings located in seismic areas, the use of unreinforced masonry, due to its low tensile strength and low ductility, is limited both by the European and the National Codes.

In Italy, the construction of load bearing masonry made with thin layer mortar and units with small dimensional tolerance in height has been recently introduced. In order to get all the necessary information about its mechanical properties and to assess its behaviour under seismic action, an experimental program has recently been carried out at the University of Padua. Fifty-one specimens were characterized by means of uniaxial and diagonal compression tests and by means of shear compression tests. The tests were performed with different values of the shear ratio on the vertical load level, with repeated load cycles at each displacement level. A comparative study was carried out on masonry made with ordinary joints and general-purpose mortar. Further tests were carried out to characterize the behaviour of the interface between units and mortar and the material properties, in order to get all the relevant data for the subsequent modelling.

KEYWORDS: thin layer mortar; in-plane cyclic tests.

INTRODUCTION

Development in the masonry industry and in the construction sector imposes the use of different typologies of unit, assembled with different types of head and bed joints, such as units with interlocking features, units with small dimensional tolerances for use with thin layer joints, etc. Even if these types of masonry are recognized by the Eurocode 6, the definition of strength characteristics should rely on databases available at a national level [1]. Traditionally only the construction of masonry made with filled head joints has been allowed in seismic zones [2], however, the latest version of the Eurocode 8 defers the permission of their use in seismic areas to each country [3]. At the same time, the use of these different typologies of masonry, built with non-ordinary joints, has not yet been regulated by the national codes [4,5]. For this reason, the investigation into the mechanical behaviour and the characteristics of masonry made with different kinds of units, joints and bonding arrangement, still constitutes a topic of interest for many researchers, as demonstrated also by some recent extensive experimental research [6]. With regard to the in-plane strength and deformability capacity of the different types of masonry made of clay units, there is great difficulty in summarizing the data available in literature, in particular for the behaviour of masonry under combined vertical and horizontal in-plane cyclic actions. The reason is that although for simple loading conditions harmonized tests procedures have been in use for a long time, different test procedures have been adopted for the determination of the shear behaviour of masonry. The lack of information about the in-plane cyclic behaviour of masonry made with thin layer joints, is due also to the fact that the widespread use of this masonry system started only a few years ago, despite the fact it has been used for a couple of decades in countries such as Germany, where it was first developed [7].

As a consequence of the introduction of this system for the construction of masonry buildings also in earthquake prone countries, it is necessary to assess its behaviour under seismic actions. In this framework, an extensive experimental campaign was carried out in order to characterize the mechanical behaviour of the new construction system, also under in-plane cyclic loading. The system was studied in comparison with other typologies of masonry walls currently adopted in practice, characterized by different configurations of head joints. In particular, masonry specimens made with interlocking system and masonry made with units with mortar pocket were tested. The tests ranged from materials, to micro and macro assemblages in order to allow the experimental assessment of the influence of the geometry and in particular of the material properties on the overall mechanical behaviour of masonry. The main purpose of the experimental study was to characterize the mechanical behaviour of the tested systems under different point of view in order to determine all the parameters needed for the subsequent analytical and numerical modelling of the systems. Namely, to survey the crack pattern evolution and experimental determination of failure mechanism under different types of loading, to determine the basic mechanical properties and constitutive laws of the material, and to assess the behaviour under in-plane cyclic actions.

EXPERIMENTAL PROGRAM

The tests were carried out at the Laboratory for Structural Material Testing, at the University of Padova. They were divided into two phases. The first phase, described by Valluzzi et al. [8], was aimed at the definition of the construction system. The mechanical behaviour of masonry made with thin layer joints was compared with that of masonry made with the same units (with tongue and groove head joints) but with ordinary bed joints. Furthermore, two different construction methods for building masonry made with thin layer joint, namely by dipping the bottom bed face of the units into the mortar or by using a mechanical device that rolls out the thin layer joint, were compared with regard to both the economy of construction (time and precision of execution, consumption of material) and the influence of the execution method on the mechanical behaviour of the masonry [9]. During the second phase, three typologies of masonry walls were studied: masonry made with thin layer joints (TM), masonry made with ordinary bed joint and interlocking units (TG), and masonry made with ordinary bed joint and units with pocket for mortar infill (Po). According to the Eurocode 6, this last typology can be classified as having filled head joints, considering that mortar was provided over a minimum of 40% of the unit width. The main objective of this second experimental phase was to assess the cyclic behaviour of masonry made with different types of head and bed joints, under in-plane loading.

The unit cross section was the same for all the unit typologies, and it was designed according to the provisions for unit geometry given by the new Italian seismic code [5]. The units contained holes having a void area equal to 43% of the gross cross-sectional area, nominal dimensions of 250x300 mm (length x width) and height equal to 250 mm for the TM units, and 225 mm for the TG and Po units. The specimens made with thin layer joints were assembled using a special pre-mixed mortar with cement binder, methyl-cellulose polymeric additives for regular water retention and fine aggregates (size 0-0.5 mm), laid by means of the mechanical device (Figure 1), in bed joints with average thickness equal to 1.3 mm. The mortar used for the reference specimens was a general purpose premixed cement-lime mortar with aggregates having maximum size equal to 4 mm, and the resulting bed joints had average thickness of about 12 mm. The experimental phase started with accurate specimen preparation and construction. Almost 150 tests on mortars and units, 70 tests on micro-assemblages for the determination of the properties of the unit-mortar interface (couplets and crossed couplets) and more than 50 tests on large assemblages (wallettes) were carried out. Table 1 summarizes the main tests carried out on small and large specimens.

Figure 1 – Edge-ground units used for the research (TM, left) and construction of a specimen (right)

Table 1 – Tests carried out on small and large size specimens

Type of specimen	Type of unit	Dimensions (mm)	Type of test	Number of tests
Couplets	TM	245x300x300	Sliding along the bed joint	9
	TG (& Po)	245x300x310		9 (+9)
Crossed couplets	TM	245x300x500	Tensile strength along the bed joint	6
	TG	245x300x462		6
Wallettes	TM	983x300x998	Uniaxial compression	6
	TG	991x300x928		6
	Po	991x300x928		6
	TM	983x300x998	Diagonal compression	6
	TG	991x300x928		6
	Po	991x300x928		6
Wallettes	TM	984x300x1250	Cyclic shear compression tests (and monotonic)	4 (+1)
	TG	992x300x1170		4 (+1)
	Po	992x300x1170		4 (+1)

BASIC MATERIAL CHARACTERIZATION

Table 2 and Table 3 summarize the main mechanical properties of the units and the mortars used: average and normalized compressive strength of the units in the direction of the vertical loads

($f_{b,m}$ and f_b) and in the horizontal direction ($f_{bh,m}$ and f_{bh}); splitting tensile strength in the direction parallel to the length and to the width of the unit calculated on the gross area ($f_{t//l}$ and $f_{t//w}$); flexural strength f_{mt} and compressive strength f_m of the mortar; elastic modulus E and Poisson's ratio ν.

Table 2 – Mechanical properties of the units

Unit	$f_{b,m}$	f_b	$f_{bh,m}$	f_{bh}	$f_{t//l}$	$f_{t//w}$	E	ν ($\varepsilon_{hl}/\varepsilon_v$)	ν ($\varepsilon_{hw}/\varepsilon_v$)
	N/mm^2	N/mm^2	N/mm^2	N/mm^2	N/mm^2	N/mm^2	N/mm^2	-	-
TM	20.42	23.49	7.57	8.71	0.434	0.586	9328	-0.22	-0.32
TG	20.96	25.15	9.10	10.46	0.349	0.526	7997	-0.17	-0.22
Po	20.43	24.51	7.95	9.14	0.370	0.611	7887	-0.14	-0.23

Table 3 – Properties of the mortars

Mortar	Water/product ratio	Curing days	f_{mt} N/mm^2	f_m N/mm^2	E N/mm^2	ν
Thin layer	0.35	28	4.43	17.68	8238	0.21
		60÷75	5.08	19.79		
General purpose	0.28	28	3.51	11.51	9507	0.154
		60÷75	4.22	14.64		

The tests for the determination of the shear strength under zero compressive stress were carried out on specimens made with two elements, according to the recently modified version of the European Standard (EN 1052-3, 2002). The specimens were tested under 0.05, 0.10, 0.20 and 0.30 N/mm^2 confining pressure. The higher values of confining loads recommended by the standard were not applied due to premature failure of the units, related to both the crushing of the loaded portion of the outer shell and to the shear failure of the unit itself. The tests were carried out by applying a monotonic load along the mortar joint under displacement control (0.01 mm/s). The vertical displacement of the two units and the dilation of the horizontal joint were measured by means of six LVDTs (±10 mm displacements). Figure 2 shows two specimens made with tongue and groove units and ordinary joints (TG) at collapse. The shear failure of the unit and the sliding failure of the joints can be compared. Figure 3 shows the shear stress-confining compressive stress diagrams that allow determining the coefficient of friction and the cohesion of the unit-mortar interface. The tensile tests on the bed joint were carried out by adapting the crossed couplet test configuration (ASTM C952-86, reappr. 1990). The load was applied monotonically until failure, under displacement control (0.01 mm/s), by means of two U shaped metallic profiles. The relative displacements of the units were measured by means of two potentiometric displacement transducers (100 mm). The failure occurred suddenly by separation of the two contact bed faces of the units for the thin layer joint specimens, at an average tensile stress equal to 0.20 N/mm^2. In the case of ordinary joint masonry the mortar adhesion was higher than the same unit internal cohesion, so that a shear failure with diagonal cracking of the units was observed, at an average tensile stress along the bed joint equal to 0.42 N/mm^2.

Figure 2 – Test of sliding along a mortar joint: failure of the unit (above), failure of the joint (below)

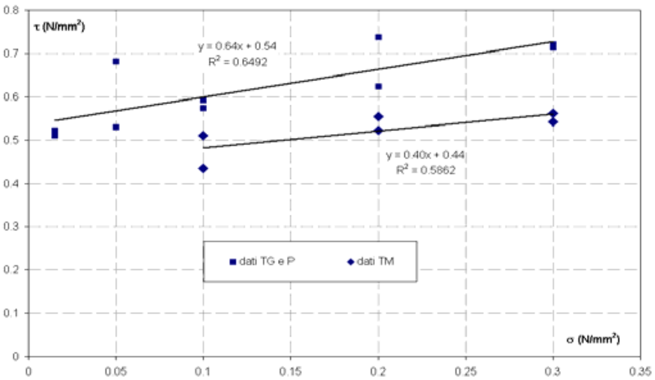

Figure 3 – Test of sliding along a mortar joint: shear-compression stresses diagrams for specimens failed along the joint

UNIAXIAL COMPRESSION TESTS

The uniaxial compression tests were carried out by means of an Amsler machine whose maximum load is 10000 kN. Two layers of Teflon were placed between each end of the specimens and the loading plates, in order to minimize friction at the ends and create a uniaxial stress state. The tests were carried out under monotonic loading, with a load increment rate of about 0.5 kN/s (EN 1052-1, 1998). On all the specimens a 10 kN preload was applied. After reaching the maximum load, the load was maintained until the 80-90% of the peak value, when possible, in order to check the load decrease caused by the propagation of damage. The specimens were instrumented with six LVDTs (±10 mm), two in the horizontal, two in the vertical direction on the main faces of the specimen, and two in the horizontal direction on the width. On some of the specimens, four strain transducers (±2.5 mm) were also used, two placed vertically (on a unit and across a mortar joint) and two placed horizontally (on a unit and across a head joint) in order to investigate in detail the deformability properties of the specimens. The results including maximum compressive stress σ_{max} (maximum applied load divided by the horizontal cross sectional area), compressive stress at which the out-of-plane buckling of the specimens started (σ_{inv}) and their ratio are shown in Table 4. The elastic modulus, E, determined between 10-40% and 30-60% of the ultimate load and Poisson's ratio, ν, evaluated on the first linear branch of the curve (10-40%), vertical and horizontal strain ($\varepsilon_{v\sigma inv}$, $\varepsilon_{h\sigma inv}$) and their ratio at the load at which the out-of-plane buckling of the specimens started, are also shown in Table 4.

Table 4 – Uniaxial compression tests results

Spec.	σ_{max}	σ_{inv}	$\sigma_{inv}/\sigma_{max}$	$E_{10\text{-}40\%}$	$E_{30\text{-}60\%}$	$\nu_{\tau max}$	$\varepsilon_{v\tau max}$	$\varepsilon_{h\tau max}$	$\varepsilon_{h\tau max}/\varepsilon_{v\tau max}$
	N/mm²	N/mm²	%	N/mm²	N/mm²	‰	‰	‰	-
TM	6.95	4.97	71	4497	4424	-0.45	1.07	-1.73	-1.60
TG	5.67	4.57	80	4924	4278	-0.36	0.99	-1.48	-1.52
Po	5.34	4.62	86	5237	4141	-0.25	0.94	-1.34	-1.56

For almost all the specimens, the crack developed starting from the main faces of the specimens, in the middle of the specimen, following the discontinuity of the head joints. Subsequently, for loads higher than 70% of the ultimate load (masonry made with thin layer joint), and 80% of the ultimate load (masonry with ordinary mortar joints), the specimens started to deform out of plane, and the trend of the displacement measured by the vertical transducers inverted, measuring lengthening (negative values) instead of shortening (positive values). In some cases, this was also made visible through the development of one or more cracks on the transversal sections. This condition evolved, with increase of cracking on the main faces of the specimens, until total collapse. In some cases, complete separation of the masonry walls into columns was noted at failure. Failure of shells was obtained only after having reached the ultimate loading, by unloading and loading again the specimens to total collapse. The failure mode was not particularly influenced by the typology of masonry used. For masonry made with thin layer joints the out-of-plane buckling was more noticeable. Figure 4 shows typical stress-strain diagrams for the three types of tested specimens.

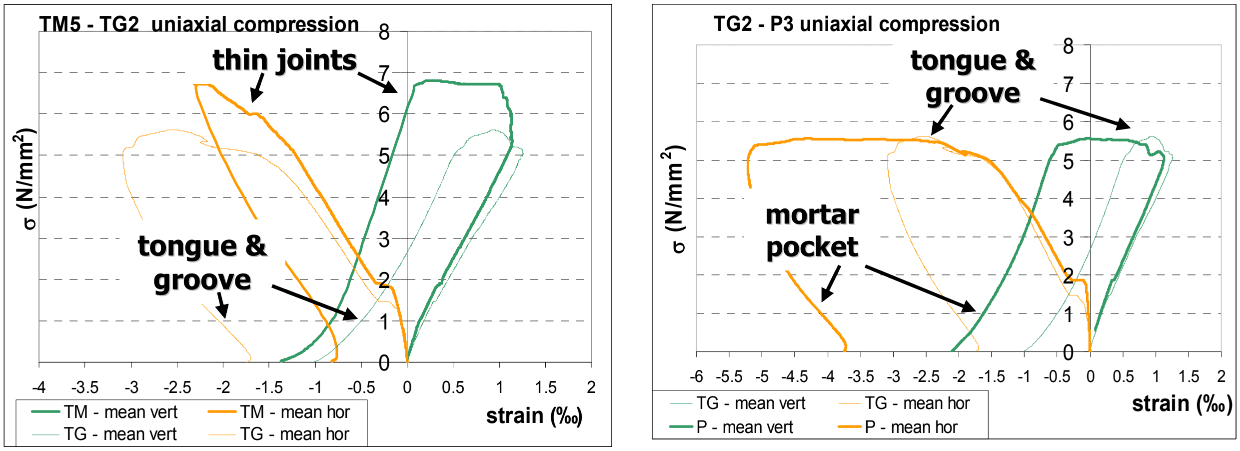

Figure 4 – Typical stress strain diagrams under uniaxial compression: comparison between masonry made with thin layer joint and ordinary bed joints (left), comparison between masonry made with tongue and groove and mortar pocket head joints (right)

The compressive strength of the specimens made with edge-ground blocks and thin layer joint (TM) was higher than in the case of the corresponding ordinary masonry. The mean increase was about 20%. Furthermore, the specimens made with thin layer joints presented lower deformability to vertical loads than the specimens made with ordinary joints. This was made evident by the higher elastic modulus (on average 6%) and by higher tendency to horizontal rather than vertical deformability (higher Poisson's coefficients, on average 24%). Regarding the comparison between specimens made with unfilled head joints (TG) and with mortar pocket (Po), it can be said that both compressive strength (average values equal to 5.67 N/mm^2 and 5.34 N/mm^2, average difference 3%) and elastic modulus (average values equal to 4278 N/mm^2 and 4141 N/mm^2, average difference 1%) were practically equal, with even lower values for the masonry walls made with mortar pocket, as also found from literature survey [7].

DIAGONAL COMPRESSION TESTS

The diagonal compression tests were carried out under a reaction frame with a 560 kN actuator and a 300 kN load cell. The load was applied by means of two steel loading shoes, whose length of bearing is about 15 cm and width is equal to the masonry thickness (ASTM E 519-81, reappr. 1988). The tests were carried out under displacement control, at a rate of 0.01 mm/s and the specimens were instrumented with four LVDTs placed along the diagonals. On some of the specimens, two strain transducers were also placed vertically and horizontally in a central block, and three potentiometric displacement transducers (100 mm) were placed across and along bed and head joints. The results including nominal shear strength, τ_{max} (maximum applied load divided by the diagonal cross sectional area), shear modulus, G, .shear strain, γ evaluated between 10-40% and 30-60% of the ultimate load, shear strain $\gamma_{\tau max}$, and the vertical and horizontal strains ($\varepsilon_{v\tau max}$, $\varepsilon_{h\tau max}$) and their ratio at ultimate load are reported in Table 5.

Table 5 – Diagonal compression tests results

Spec.	τ_{max}	$G_{10-40\%}$	$G_{30-60\%}$	$\gamma_{10-40\%}$	$\gamma_{30-60\%}$	$\gamma_{\tau max}$	$\varepsilon_{v\tau max}$	$\varepsilon_{h\tau max}$	$\varepsilon_{h\tau max}/\varepsilon_{v\tau max}$
	N/mm^2	N/mm^2	N/mm^2	‰	‰	‰	‰	‰	-
TM	0.206	927	753	0.039	0.086	0.248	0.281	-0.033	-0.123
TG	0.270	1002	816	0.062	0.124	0.342	0.373	-0.032	-0.099
Po	0.537	1402	1213	0.071	0.154	0.399	0.459	-0.061	0.124

The collapse occurred suddenly with the formation of a diagonal crack along the loaded diagonal, with a stepped pattern that follows the head and bed joint pattern. In a few cases some units also cracked along the loading direction. The displacements along the horizontal diagonal were much smaller than in the vertical direction. Due to the asymmetry of the loading application, in fact, the cohesion of the mortar unit interface, the friction along the joint and the possible presence of mortar droppings inside the holes hindered the dilation in the horizontal direction, whereas the effect of the direct application of load was evident in the vertical direction. The stress-strain diagrams (Figure 5) show the elastic-brittle behaviour of the specimens that is due, however, also to the test configuration itself.

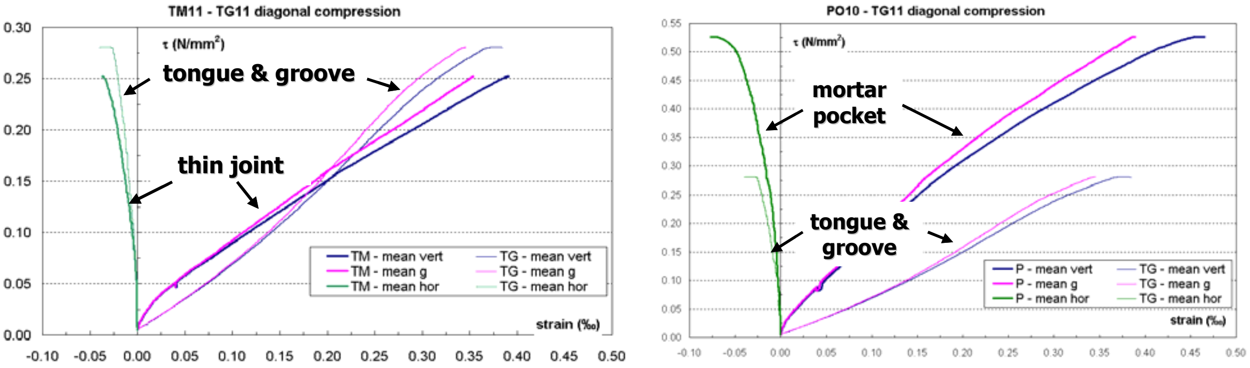

Figure 5 – Typical stress strain diagrams under diagonal compression: comparison between masonry made with thin layer joint and ordinary bed joints (left), comparison between masonry made with tongue and groove and mortar pocket head joints (right)

In the case of masonry made with thin layer joints (TM), the joints generally remained adherent to just one of the unit bed faces. In the case of ordinary masonry (TG and Po), the mortar joints cracked following the discontinuity of the head joints or at the midpoint of the adhesion surface. The resisting mechanisms thus turned from mortar adhesion to one involving the internal cohesion of the mortar itself as well. The presence of mortar droppings in the unit holes allowed a ‘dowel action’ effect. In some cases, the general purpose mortar used for the ordinary masonry specimens exhibited adhesion properties that were even higher than the internal cohesion of the unit, thus at the end of the test some portions of the unit were detached from the rest of the unit. The mortar pockets, in the specimens Po, cracked close by the horizontal joint and remained completely adhered to the unit where the recess for mortar filling is found. In this case, resisting mechanisms related to the internal cohesion of the mortar pocket and to friction with the unit lateral faces were activated. The nominal shear strength, τ_{max}, was lower for masonry made with thin layer joints (TM) than for masonry made with ordinary bed joint (TG; average decrease 33%), showing an inverted trend compared to previous experimental work [8]. This may be due to the very high bond strength developed by the unit-mortar interface in the case of general purpose mortar, as revealed by inspection of the specimens and by the results obtained during direct tensile tests. Regarding the comparison between masonry made with unfilled head joints (TG) and with mortar pocket (Po), the nominal shear strength (average values equal to 0.27 N/mm^2 and 0.54 N/mm^2 respectively) is exactly double in the case that the head joint is filled, in agreement to what can been found in literature [7] and due to the resisting mechanism developed along the head joint, in this type of test.

SHEAR-COMPRESSION TESTS

The set-up for the execution of the shear compression tests was created purposely on the basis of the most common test configurations and following the main existing experimental experiences [10]. The specimens were tested with cantilever type boundary condition, with fixed base and top end free to rotate, by applying a centred and constant vertical load equal to 17%, 21%, 27% and 33% of the measured maximum compressive strength. Horizontal cyclic displacements, with increasing amplitude and with peaks repeated three times for each displacement amplitude, were applied at a frequency of 0.004 Hz. The displacement history was determined by fixing a reference critical displacement δ_{cr}=2 mm (inter-storey drift equal to 0.17%). One reference specimen per type was tested under monotonically increasing displacement. The specimens were designed to reproduce the typical masonry walls behaviour, presenting both flexural and shear failure mechanisms. During the in-plane cyclic tests the attainment of four main limit states, which can be used to idealize the masonry wall behaviour [11], were observed. First, as a result of rocking, flexural cracking was observed, defined by the initiation of horizontal cracks, generally opening in the first mortar bed joint between the specimen and the lower concrete beam. At this point, the response of the wall to the horizontal imposed displacement changed, with a deviation from the first linear branch of the hysteresis loops (flexural cracking limit, H_f, δ_f). Second, the formation of the first significant diagonally oriented shear crack was observed, and the slope of the resistance envelope changed again (crack limit, H_{cr}, δ_{cr}). The attainment of the maximum resistance H_{max} occurred at a corresponding displacement level δ_{Hmax}, and after developing their full displacement capacity, the specimens reached the ultimate state at the attainment of the maximum displacement δ_{max}, to which a consequent value of residual lateral resistance H_{dmax} corresponded. Table 6 summarizes the ratio between the lateral load and lateral displacements and the corresponding values of rotation angle at the relevant limit states, including the value of lateral resistance H_{du}, ultimate displacement δ_u and rotation angle ψ_u attained when a maximum strength degradation of 20% occurred. The values of tensile strength f_t evaluated by means of the Turnsek and Cacovic's [12] criteria, and the experimental value of the shear modulus G_{exp}, as evaluated by the strain measured on the specimens are also reported. The values reported in Table 6 are mean values obtained from tests carried out at different pre-compression levels.

Table 6 – Summary of the main results obtained by means of shear-compression tests

Spec.	H_{cr}/H_{max}	H_{du}/H_{max}	$\delta_{cr}/\delta_{Hmax}$	δ_u/δ_{Hmax}	δ_u/δ_{cr}	ψ_{cr}	ψ_{Hmax}	ψ_u	f_t (N/mm^2)	G_{exp} (N/mm^2)
TM	0.85	0.94	0.37	1.33	3.73	0.32	0.82	1.08	0.249	653
TG	0.96	0.87	0.67	1.24	2.16	0.86	1.26	1.55	0.247	1016
Po	0.95	0.82	0.67	1.44	2.55	1.04	1.49	2.19	0.274	1098

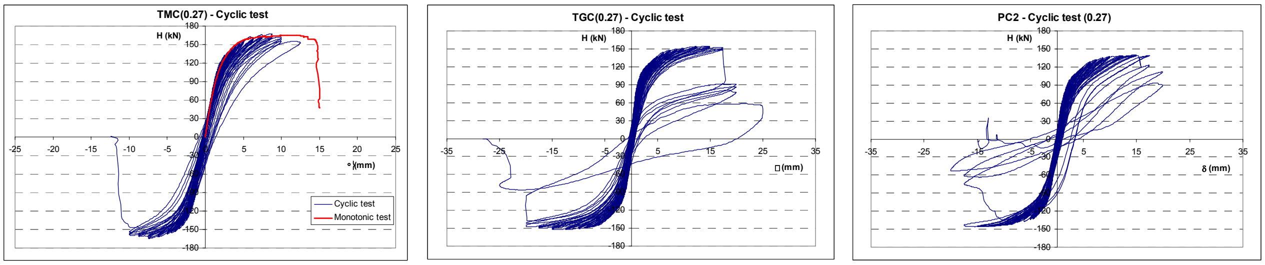

Figure 6: Lateral load-displacement diagrams for specimens TM (left), TG (centre) and Po (right) tested under 27% ratio of applied vertical load to maximum compressive strength

The opening of the first flexural crack at the lower mortar joint occurred at a level of about ±2 mm, ±1.6 mm, and ±1.8 for specimens TM, TG and Po, respectively. Afterwards, the specimens made with thin layer joints had a low tendency to a rocking type of behaviour, which developed into a mechanism where each block singularly was rotating following the imposed displacement around its own centroid, whereas the rigid body behaviour was more evident for specimens made with ordinary joints. The first cracks (specimens TM) developed for about double values of displacements, generally in the central part of the specimens, whereas for specimens TG and Po they developed for values of displacements definitely higher (from 4.5 mm to 12.5 mm), and sometimes occurred at the compressed toe of the specimens, with complex patterns associated with the crushing of the units. After that crack, the lateral resistance still increased, but to a limited extent. On average, the displacement at maximum resistance was 2.7 times larger that at shear cracking limit for specimens TM, and about 1.5 times larger for specimens TG and Po, depending on the ratio of the vertical load applied. However, due to the higher value of δ_{cr}, the values of drift for the specimens made with ordinary mortar were higher, indicating a higher displacement capacity associated with lower initial stiffness and a rocking type of behaviour. At the maximum resistance, a clear crack pattern following the inclined compressed struts over the height of the specimen was already visible. With this type of test, due to the activation of different mechanisms and due to specific material properties, it was not possible to notice significant differences in the values of tensile strength. The dissipation capacity, evaluated both from the input and dissipated energy and the corresponding damping, and from the analysis of the hysteresis loops, dominated by a 'pinching' effect, was low for all the types of masonry.

CONCLUSIONS

In the present contribution, some phenomenological analyses of different failure modes of masonry made with different types of head and bed joints, depending also on the type of testing, are presented. The experimental results obtained were also used to assess some analytical models available for the prediction of the ultimate capacity of masonry walls under in-plane uniaxial compression and shear compression loading [7]. The results have been compared with others collected in literature, on different types of clay block masonry walls, and are being used as a reference database for modelling and standardization purposes.

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